A Study of the Structure of the Near-Coastal Zone Water Column Using Numerical Simulations

Jeffrey R. Koseff
Joel H. Ferziger
Stephen G. Monismith

Environmental Fluid Mechanics Laboratory
Department of Civil and Environmental Engineering
Stanford University
Stanford, CA 94305-4020

phone: (650) 723-3921 fax: (650) 725-8662 email: koseff@ce.stanford.edu
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LONG-TERM GOAL

Our long-term goal is to understand how flows in near-coastal zone (20m to 100m) respond to a variety of forcing mechanisms including wind stresses, tidal pressure gradients, surface waves, surface heating and cooling, surface wave-bottom current interaction, and tidally generated bottom boundary currents. Because the nature of this response varies throughout the water column and depends strongly on the non-linear coupling of stratification, turbulence and flow structure characterizing the structure of the water column in this environment is a very difficult field measurement task.

OBJECTIVES

It is possible to gain some insight into the physics, and into our ability to model or parameterize the physics, by looking at a more idealized version of this problem using a variety of numerical simulation approaches.We plan to develop Large Eddy Simulation Models of the flow structure in the stratified water column in the near-coastal zone which are typically subject to surface heating fluxes, wind stirring, and tidally generated bottom turbulence. Using these simulation tools we shall study the physics, and how to parameterize it, for two related flow problems. In particular:

a) Stratified tidal flows, i.e., stratified flows with oscillating pressure gradients;
b) Wavy turbulent flows, i.e., channel flows with waves.

APPROACH

Two codes have been developed for doing the proposed simulations. The first is a parallelized Navier-Stokes code for solving stratified, turbulent channel flows. This code was originally developed and implemented on the 400 node Intel Paragon XP/S supercomputer at SDSC by Garg et al. (1994, 1995). The second code is a modified form of the fractional step finite-volume Navier-Stokes code developed by Zang et al. (1994) for generalized curvilinear co-ordinates. For turbulent cases, we used a large eddy simulation approach that models the sub-grid stresses with a dynamically determined Smagorinsky constant.

WORK COMPLETED

Wavy Boundary Problem

In this part of the study, numerical simulations of laminar and turbulent open channel flows with a moving wavy surface that has the form of a second order Stokes wave were performed. A constant tangential stress is imposed at the top. It drives a mean current that interacts with the surface wave to generate Langmuir circulations. In our model, the Navier-Stokes equations are solved in (two and three dimensions) in a curvilinear coordinate system, with kinetic and dynamic boundary conditions applied on the wavy surface. An orthogonal transformation is used to map the wavy physical domain into a rectangular computational domain. The numerical method is a modified version of the fractional step method of Zang et al., (1994) for a generalized curvilinear coordinate. For turbulent cases, we used a large eddy simulation approach that models the sub-grid stresses with a dynamically determined Smagorinsky constant. The 2D and 3D numerical results were compared with those from the simulations based on the Craik-Leibovich (CL) theory in a rectangular domain.

Stratified Tidal Flows

We are now in the process of implementing a parallelized Navier-Stokes code for solving stratified, turbulent channel flows on an SGI parallel machine using MPI, and by partioning the grid across processors. Some preliminary runs have been done.

Stratified Shear Flows

We have also performed Direct Numerical Simulations (DNS) of stratified sheared homogeneous turbulence over a wide range of initial dimensionless shear rates and turbulent Reynolds numbers. These simulations were performed to test the published result of Jacobitz et al (1997) that the stationary Richardson number is a function not only of the Reynolds number but also of the dimensionless shear rate. The simulation results were also used to test some new ideas for the scaling of stratified turbulence.

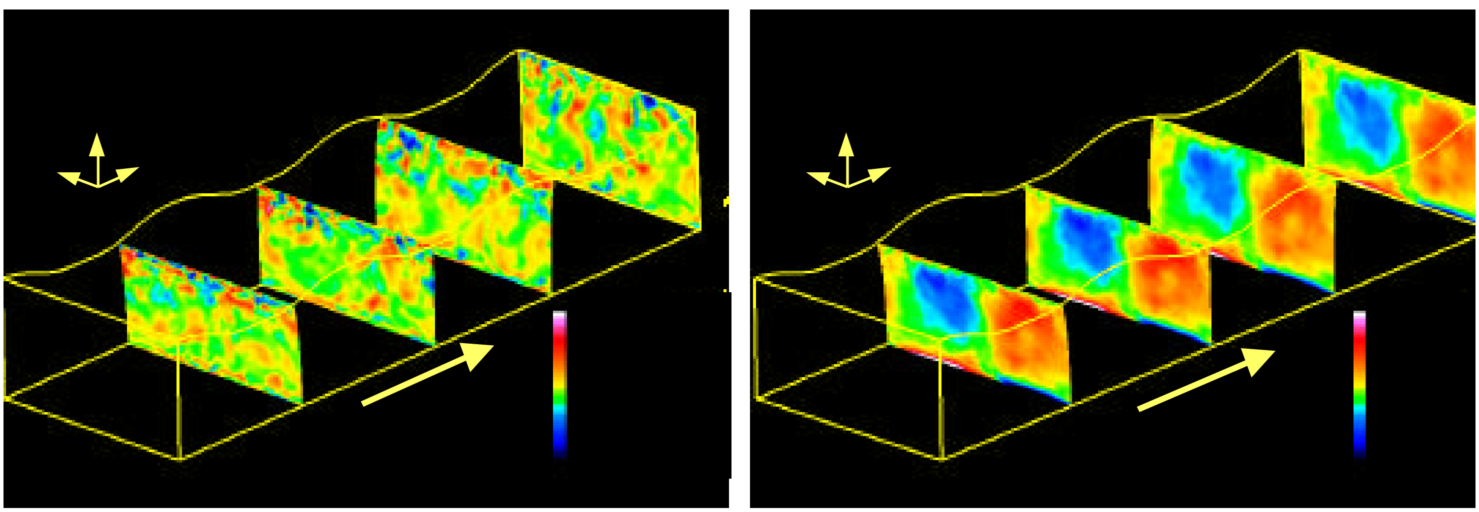
RESULTS

Wavy Boundary Problem

1. First, two dimensional free surface flows under a second order Stokes wave were examined. Analytical solutions for the inviscid flow and numerical solutions for the viscous flow were obtained. Two components of the wave field important to Langmuir circulations were identified: the Stokes drift caused by the irrotational wave motion, and the Eulerian mean flow induced by the top wavy boundary layer.

2. For the three-dimensional laminar wavy flow simulations, the initial perturbations grow exponentially in time. Higher modes with short wavelengths develop first. They later combine and large counter rotating Langmuir cells form in the final equilibrium state. As observed in the field, the Langmuir cells are asymmetric, the downwind velocity being greater at the convergence zone than at the divergence zone. They coexist with the wave field and are modulated by the surface wave.

3. These numerical results were compared with those from simulations based on the Craik-Leibovich (CL) theory in a rectangular domain. It was shown that, in addition to the Stokes drift included in the CL theory, the Eulerian mean flow induced by the surface wavy boundary layer is also important. Including its effects in the simulation based on the CL theory is essential to predicting the correct quantitative properties of Langmuir circulations, especially the pitch, which is the ratio of the maximum downwind jet velocity to the maximum downwelling velocity. When the wave-induced stress is included, excellent agreement is achieved between the computed streamwise-averaged wavy flow and that predicted by the CL theory.



(a) (b)

Figure 1: Instantaneous (a) and Time-Averaged (b) Vorticity Contours for the 3-D Wavy Turbulent Case. The Wind Direction is indicated by the large arrow. The yellow contour corresponds to zero vorticity with red being positive and blue being negative.

4. For the turbulent case, the Langmuir circulations are embedded in a much stronger, more chaotic instantaneous field; nonetheless, they can be clearly identified by time averaging. This is illustrated in Figure 1 which shows vorticity contours for a 3-D wavy turbulent case simulation with parameters based on typical conditions found in the ocean (except for viscosity and wave slope).Figure 1(a) shows the instantaneous vorticity on spanwise vertical planes at four streamwise locations. We see that the flow exhibit rich turbulence structure with a continuous spectrum of length scales. Large scale coherent structures are hard to find. However, when the flow is averaged

locally over time (Figure 1b), two counter-rotating vortices, i.e. Langmuir circulations can be clearly identified, as shown in the second figure. It can also be observed that the mean vorticity is only about one-tenth of the instantaneous vorticity in magnitude. That is why the Langmuir circulations are almost completely hidden by the chaotic instantaneous motions.

5. Relative to non-wavy stress-driven open channel flow, the streamwise turbulent fluctuations are weaker but the spanwise and vertical perturbations are stronger. Unlike the open channel flow turbulence, in which the streamwise momentum is transported mainly by the turbulent motion, in “Langmuir turbulence”, the mixing due to the turbulence and the mean Langmuir circulations are approximately of equal importance. The mean flow is also modified: close to the bottom wall, the logarithmic region is destroyed by the penetration of the Langmuir circulation. Near the top surface, Langmuir circulations destroy most of the logarithmic profile leading to a more uniform mean current.

6. The turbulent kinetic energy budget shows that in the top-surface layer, the production rate is enhanced in Langmuir turbulence. The pressure transport term is also significant in this region; this is not the case for turbulent Couette flow. Although the Langmuir circulation structure is similar in turbulent wavy flow and the flow obtained using CL theory, significant quantitative differences are observed. For a Langmuir number of 0.3, CL theory produces stronger Langmuir cells but weaker turbulence.

Stratified Shear Flows

Over the wide range of Richardson (Ri), dimensionless shear number (S*), and Reynolds (Re) numbers we found the following results:

1. At low Reynolds number the stationary Richardson number depends on both the Reynolds number and the dimensionless shear number. At higher Reynolds number, however, we established that the dimensionless shear number (shear rate times turbulent kinetic energy divided by dissipation rate) evolves to a constant (around 11), regardless of its initial value, and that the stationary Richardson number varies only with Reynolds number. We found that as the shear rate increased, the transfer of energy to higher wavenumbers by vortex stretching increased, resulting in increased dissipation at these wavenumbers. As a result S* remained constant independent of the magnitude of the applied shear.

2. For the high Re equilibrium flows, we found that the turbulent Froude number (Fr_t) is a constant independent of S*. We developed an Fr_t -based scaling which predicts the final value of S* quite well over a range of Re. Based on this, we showed that Fr_t is a more appropriate parameter for describing the state of stratified turbulence than the gradient Richardson number which is more commonly used in turbulence models of stratified flows.

IMPACT/APPLICATIONS

The simulations completed demonstrate the intrinsic value of DNS and LES in that it allows us to calculate each term in a model or parameterization of the extant physics. Evaluation of existing turbulence closure models or commonly used sub-grid-scale parameterizations is therefore a lot more complete than with experiments alone. Our simulations of the channel flows are the first important step in developing a code for studying the evolution of the density structure of the water column in the near-coastal ocean. Once completed this code will be a valuable research tool for use in conjunction with field work currently underway involved in measuring flowfields in the near-coastal ocean.

TRANSITIONS

The numerical data-bases developed have been analyzed by the PI's in other research projects and the data has been used by researchers at other institutions.

RELATED PROJECTS

Shear Production and Dissipation in a stratified tidal flow - ONR - (Monismith PI)
An Experimental Study of a Breaking Interfacial Wave - NSF- (Koseff PI)
Chemical Sensing in the Marine Environment -ONR - (Monismith PI)

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